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Sarfraz Ali
University of Witwatersrand, South Africa

Fawad Akram
National University of Sciences & Technology, Pakistan

Abdul Qudoos Khan
University of Witwatersrand, South Africa

Misba-Hafsa
National University of Sciences & Technology, Pakistan

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Sarfraz Ali,
School of Mining Engineering, University of Witwatersrand, Johannesburg, South Africa
sarfrazengr@yahoo.com

Fawad Akram
National University of Sciences & Technology, Islamabad, Pakistan
Fawadakram@gmail.com

Dr Abdul Qudoos Khan
School of Mining Engineering, University of Witwatersrand, Johannesburg, South Africa
aqkhakwani@hotmail.com

Misba-Hafsa,
National University of Sciences & Technology, Islamabad, Pakistan
Misba_kiran@hotmail.com

ABSTRACT

Topographically, Pakistan comprises three major areas; Northern Highland Area, Indus Basin and Baluchistan Plateau. Its elevation varies from Mean sea Level (0 meter) at south to 8619 meters in the North at K-2 Peak. Northern Highland Area, generally sloping southwards includes Himalayan, Karakorum and Hindu-Kush ranges covering approximately an area of 155,831 square kilometers. Indus Basin stretches from foothills of Northern Highland Area to Arabian Sea in south covering approximately an area of 346,259 square kilometers. Baluchistan Plateau in the West and South comprises mountain ranges of Koh-i-Suleman, Kirther, blow-outs of coralline and lacustrine deposits along coastal belt and covers approximately an area of 347,190 square kilometers. Climate of the country varies from tropical to temperate with rain fall variation of as little as 10 inches a year in South to 150 inches a year in the North. Any rainfall surges in the North frequently unleash floods along the Indus Basin. Continuous deforestation and fires in Northern Highland Area, growing housing projects alongside water channels in the backdrop of global warming and climate change has enhanced frequency and severity of floods in Pakistan.

The year 2010 witnessed the worst flood in the history of Pakistan. The causal factors of this rare event are attributed to the amalgamation of two weather systems over Hindu-Kush and Karakorum ranges in the North. The resulting outburst in the realm of denuded landforms graduating from North to South brought about the hydrological extremes never seen before. The event was accompanied with landslides along the slopes washing away numerous houses, over-flowing water channels destroying habitats in the flood plains, precious crops, bridges, and endangered barrages and dams. While scars of a little less similar phenomenon in year 1992 due to cloud burst in Kashmir are still visible on the face of Nation, this flood caused 1985 deaths, 2946 injured; 20 million people were left homeless and destroyed 2.2 million hectares of cropped area, while damage to communication infrastructure is estimated in billions of dollars. The study encompasses geotechnical aspects of landform distribution, climatic changes and hydrological responses.

INTRODUCTION

Pakistan with an area of 803943 square kilometres (km^2) and population of around 180 million is one of the major countries located in South Asia. It is surrounded by India in East, Iran in Southwest, Afghanistan in West and Northwest, and China in the North. It is an extremely diverse country from many viewpoints. Geographically, the country is located at the confluence of trade routes between Europe and Asia. Geologically, it marks the subduction zone between Indian and Eurasian tectonic plates making this part as one of the most seismically active zone. The continuous subduction phenomenon has contributed to some of the most devastating earthquakes of the human history.

Climate of the country varies from tropical to temperate with rain fall variation of as little as 10 inches a year in south to 150 inches a year in the North. Any rainfall surges in the North frequently unleash floods along the Indus Basin. Continuous deforestation and fires in Northern High land area, growing housing projects alongside water channels in the backdrop of global warming and climate change has enhanced frequency and severity of floods in Pakistan. Year 2010 witnessed the worst flood in the history of Pakistan. The causal factors of this rare event are attributed to the amalgamation of two weather systems over Hindu-Kush and Karakorum ranges in the North. The resulting outburst in the realm of denuded landforms graduating from North to South brought about the hydrological extremes never seen before. This paper covers geotechnical aspects such as orientation & behavior of water channels, type & efficacy of flood control & protective infrastructure during recent extreme floods in Pakistan.

TOPOGRAPHIC SETTING

Topographically, Pakistan comprises three major landforms; Northern Highland Area, Indus Basin and Baluchistan Plateau. Northern Highland Area consist of snow covered Karakorum, Himalaya and Hindu-Kush mountain ranges with elevation as high as 8619 meters. This area, generally sloping Southwards spreads over an area of 155,831 square kilometers. In the Northwest and West, Koh-i-Sulaiman Range is located with elevation varying from 2000-3487 meters. Baluchistan Plateau in the West and South comprises mountain ranges of Koh-i-Suleman, Kirther, blow-outs of coralline and lacustrine deposits along coastal belt and covers approximately an area of 347,190 square kilometers.

Indus Basin stretches from foothills of Northern Highland Area to Afro Asian Ocean in south covering approximately an area of 346,259 square kilometers, Figure 1. These mountain ranges with narrow valleys and steep slopes are virtually the catchment areas of the Indus basin hosting most of the population of Pakistan. All the major rivers originating from these mountains ranges traverse across the Indus basin till they discharge in to Afro Asian Ocean. Indus Basin is thus regarded as flood plains of these rivers.

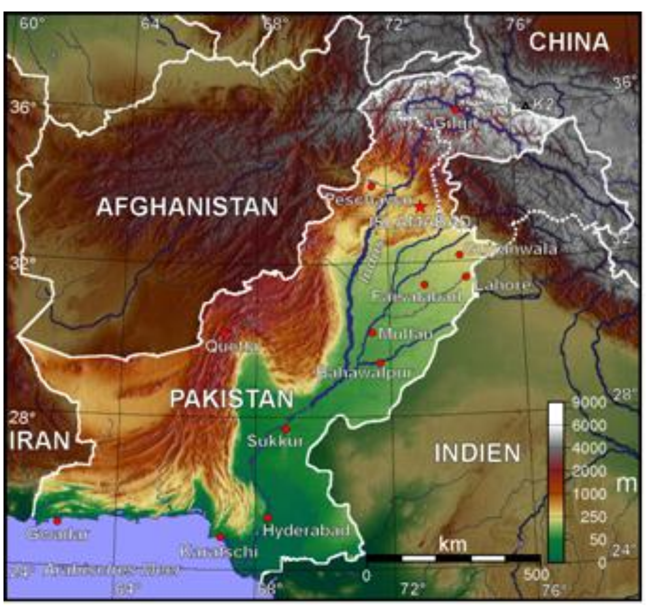

Fig. 1. Topography of Pakistan; Rivers shown in blue line, Indus Basin in green colour, major population centres shown in red circles (source: Wikipedia.org)

CLIMATE AND GLOBAL WARMING

Climatically, the country is exposed to various climate systems in the region. In an event of more than one system combining or overlapping over mountain ranges results into cloud bursts. Such phenomenon result into unprecedented downpour over an area that forms the catchment area of all the major rivers. Hydrological behaviour of the resulting run-off while traversing through the flood plains is devastating floods in entire Indus Basin.

Effect of global warming on the climate of Pakistan is manifold. At regional scale it has affected weather systems in Bay of Bengal, Arabian Sea and Afghanistan which has a direct bearing on monsoon season of Pakistan. Combination of multiple weather system was the major causal factor attributed to 2010 flood. At national level, global warming has affected the snow melting process of Himalaya, Hindukush and Koh-e- Sulaiman Mountain Ranges which also serve as the catchment area for Indus Basin.

DEMOGRAPHIC LAYOUT

Demographically, population density in the immediate vicinity of major rivers and flood plains is as high as 250 persons per square kilometre. Most of the population is concentrated around water channels and in the active flood plains, Figure 2. In all circumstances of more than usual rains, losses to public lives are therefore quite always high.

Fig. 2. Map showing population density of Pakistan; most of the 180 million population is located in Indus Basin (www.bestcountryreports.com/Population_Map_Pakistnan)

FLOODING MECHANISM

Floods in Pakistan can be categorized with respect to their nature and location. Most common are *Riverine Floods* which are in main Indus Plain and its adjacent catchments. The hill torrents on either side of Suleiman Range, Balochistan and Western Punjab (D.G. Khan and Rajanpur) generally result in *Flash Floods*. Inadequate drainage facilities in urban centres cause *Urban Flooding*. Cyclonic activities, which are prevalent before and after the monsoon incursions, produce *Coastal Flooding*. Climate change and global warming results in excessive retreat of glaciers which builds glacial lakes behind the moraine; these lakes may burst causing *Glacial Lake Outburst Flood* (GLOF). Meteorologically, there are two situations which may cause floods in Pakistan.

First Scenario

In the first situation, the seasonal low is a semi-permanent weather system (situated over South Eastern Balochistan, South West Punjab, adjoining parts of Sindh) which intensifies and causes moisture from the Arabian Sea to be brought up to upper catchments of Chenab and Jhelum rivers, Figures 3 and 4.

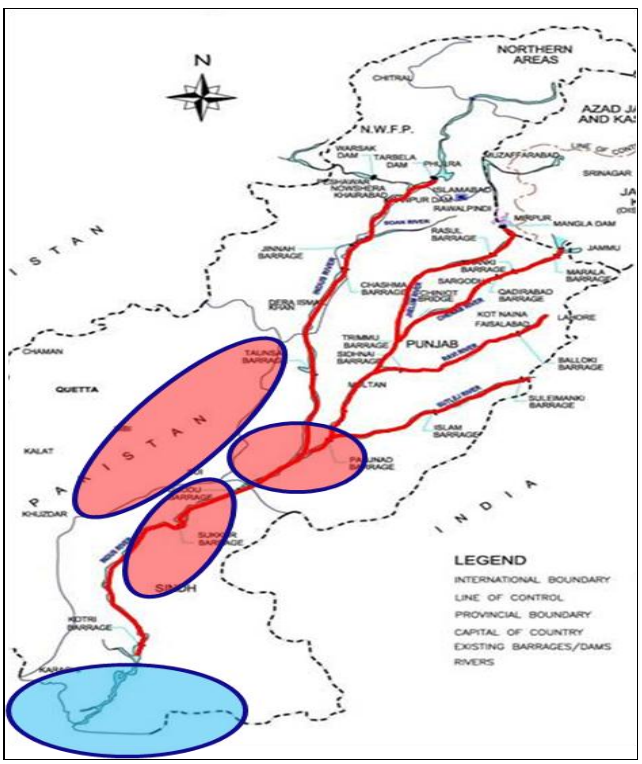

Fig. 3. Moisture from Arabian Sea moves upwards to central Pakistan

Second Scenario

Situation for more severe floods is linked with the monsoon low / depression system which originate in Bay of Bengal region, moves across India in generally west/ north-westerly direction to arrive over Rajasthan or adjoining states of India. From Rajasthan, it is nourished from Arabian Sea and moves further north over Chenab, Mangla or Khyber Pakhtunkhwa area. Complete cycle along with historical propagations is illustrated in Figures 5 through 9.

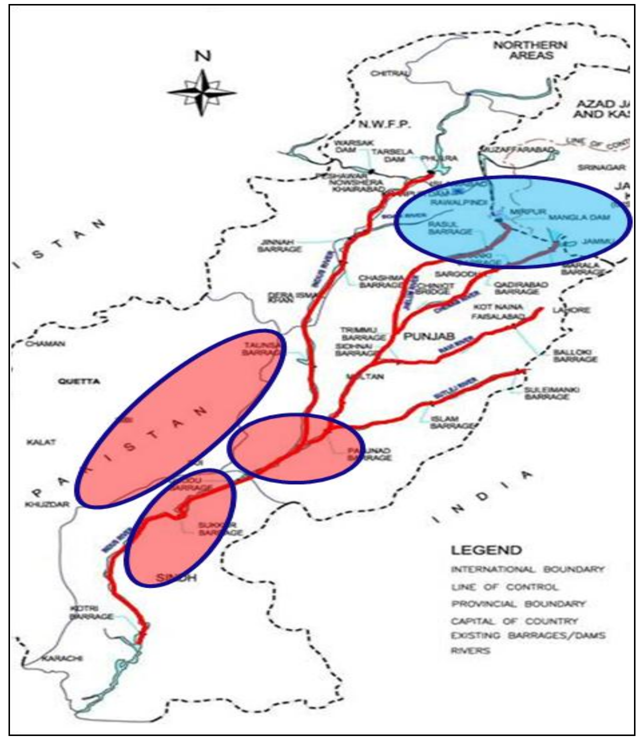

Fig. 4. Moisture from Arabian Sea reaches central and upper parts of Pakistan which is catchment area of rivers of Indus Basin

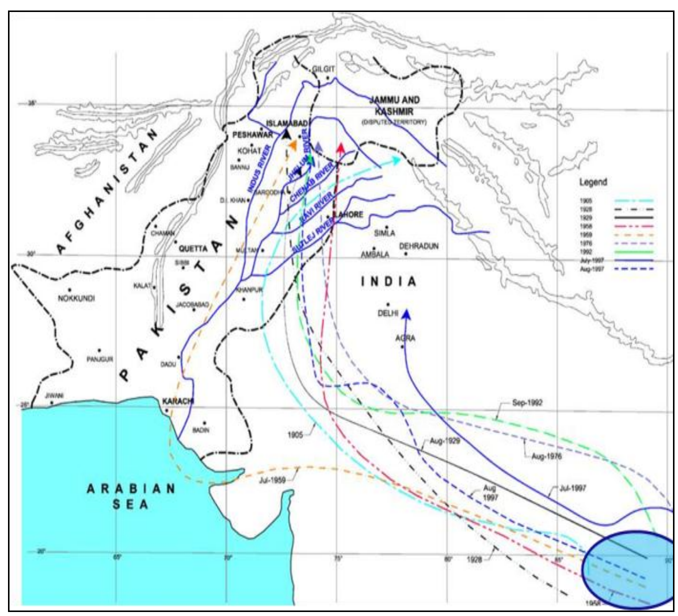

Fig. 5. Monsoon low develops in Bay of Bengal and moves towards west and north

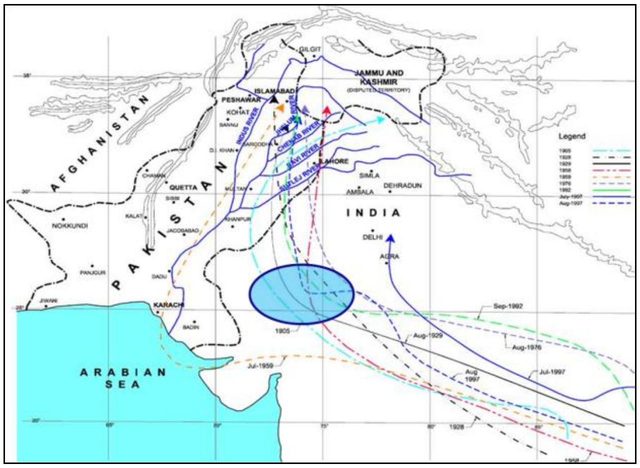

Fig. 6. Monsoon low developed in Bay of Bengal moves towards Rajasthan, India

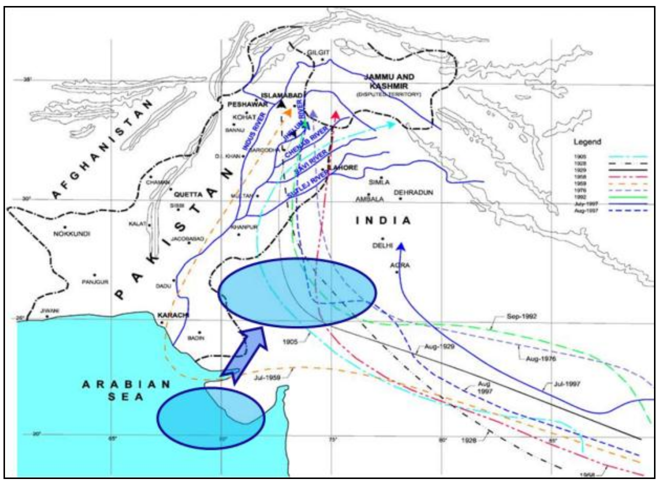

Fig. 7. Monsoon low develops in Arabian Sea and moves upwards

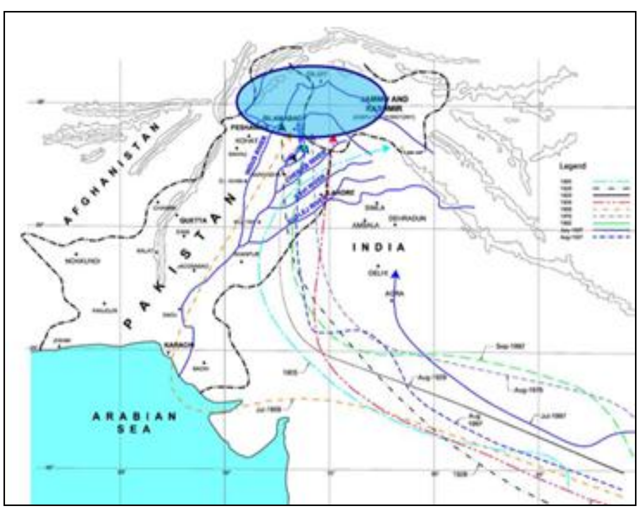

Fig. 8. Two monsoon low systems join together in northern Pakistan causing heavy downpour

In 2010 the monsoon wave adopted more or less the same path as of 1959; however the wave went deeper in Arabian Sea as shown in Figs. 5 through 9. The moisture of Arabian Sea which used to experience dissipation while moving from the sea to Rajasthan previously, this time enriched the propagating monsoon with its full moisture content. Naturally due to longer propagation path the time of this wave to reach Himalayas was delayed, and during this delay the weather system of Afghanistan matured and adopted an easterly approach due to low pressures over Himalayas. Merger of both the weather systems when viewed in time domain played havoc with water management system of Pakistan which is designed on the concept of dissipation in Indus Basin through Time Lags.

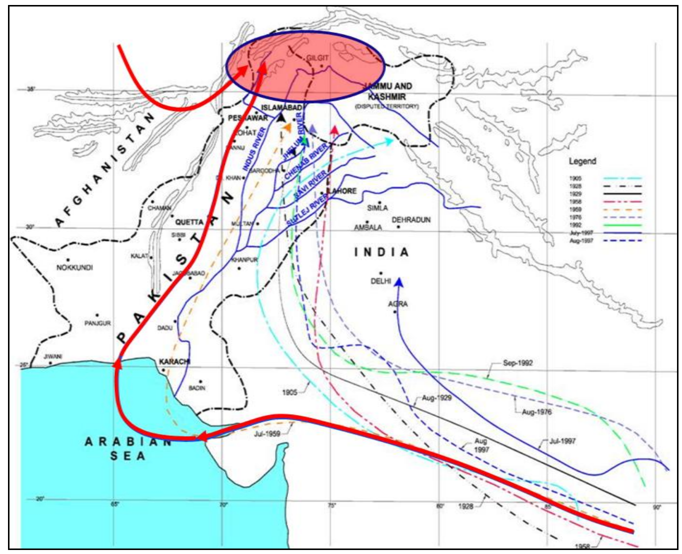

Fig. 9. Weather low system from Afghanistan also joined the two low monsoon from Bay of Bengal and Arabian Sea and further increased the downpour in Northern Pakistan

BEHAVIOR OF RIVERS AND FLOOD PLAINS

At its origin, Indus Basin is served with five rivers, Figure 10. From North to South these are named River Indus, Jhelum, Chenab, Ravi, and Sutlej/Beas. At Punjnad, almost in the central part of Indus basin, all five rivers merge into one called thereafter Indus River. Some characteristics of each river are described in the ensuing paragraphs.

River Indus

River Indus and other snow fed rivers are also likely to experience flooding due to heat wave in early summer. This phenomenon occurred in June 2005 and was followed by early monsoon rains that caused wide spread flooding in KPK. Floods in upper Indus generally result from heavy precipitation in hilly catchment of lower Himalayas and Hindu Kush which have limited valley storage. Superimposed upon significant snowmelt base flow, these conditions cause very heavy floods. Lower Indus receives combined flows of Upper Indus and its left and right bank tributaries. Floods in this reach may occur from July-October. The river can be in high flood for a period exceeding one month.

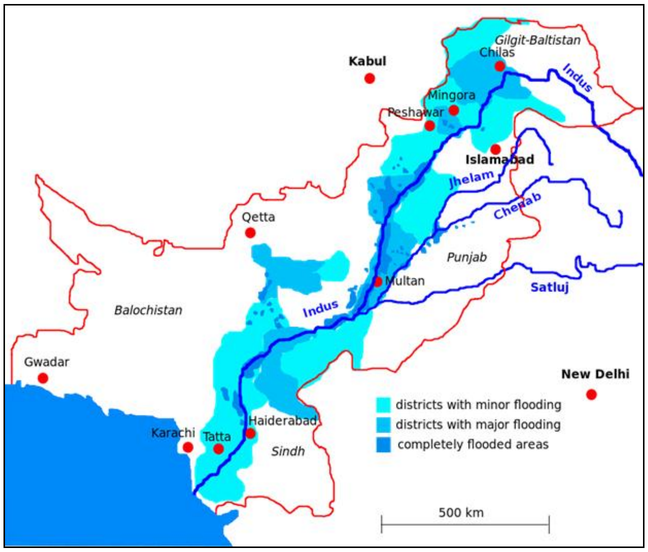

Fig. 10. Major rivers in Indus Basin
(Source: *www.defence.pk/forums/pakistan-floods)*

River Jhelum

The intense rainfall in the catchments can produce exceptionally high flood peaks. The 33,280 square kms catchment of River Jhelum has produced three recorded floods in excess of 28,000 m³/sec in last 75 years, with the latest in September 1992. The estimated Probable Maximum Flood (PMF) for the river varies from 48,000 - 70,000 m³/sec at the recording station. Major catchment area of River Jhelum above Mangla is between 4,000-12,000 feet above Mean Sea Level. This results in early snow-melt runoff from February, reaching its peak in early June. High floods in the river, however, result from heavy rainfall in catchment area during the monsoon season of July to September. Though, Mangla Dam (with estimated live storage capacity of 4.54 MAF) being an irrigation replacement project does not have any storage specifically allocated to flood control, yet during early part of its filling, till about early August, it can significantly help in flood regulation.

River Chenab

Floods in River Chenab generally result from heavy precipitation in the hilly catchment areas in lower Himalayas with limited valley storage. Snow melt flow reaches peak in early July. This, however, is not a significant factor contributing to high floods during August and September. Manipulation of hydropower projects by India with significant storage on River Chenab can also result in a flood like situation for a certain period of time affecting significant area adjoining the river course.

River Ravi

Flooding in River Ravi generally results from excessive rainfall in the mountainous catchments in India, and sub-mountainous areas drainage into lower river within Pakistan. Snow melt makes no significant contribution to flood peaks in River Ravi. The snow melt flows normally occur in the spring, falling off before the monsoon rains begin in June / July.

River Beas / Sutlej

Floods in Rivers Beas and Sutlej result from intensive rainfall in catchment areas within India. Occurrence and severity of floods in this river is greatly altered by the construction of upstream dams (Pong Dam on River Beas and Bhakhra Dam on River Sutlej) in India during 1963-1977. However, when these reservoirs are full, some late monsoon rains can still bring down large flood flows into Pakistan

CLASSIFICATION OF FLOOD LEVELS

Water and Power Development Authority (WAPDA) has categorized the floods in different levels with a view to assist all stake holders to take corrective measures according a unified policy. The classification is shown in Table 1.

Table 1. Flood Classification (WAPDA Report, 2010)

Flood Flow	Flood Classification
Up to 2.0 Lac Cusec	Normal
Up to 3.0 Lac Cusec	Low
Up to 5.0 Lac Cusec	Medium
Up to 7.0 Lac Cusec	High
Up to 9.0 Lac Cusec	Very High
Above 9.0 Lac Cusec	Super

2010 FLOOD CLASSIFICATION AT VARIOUS LOCATIONS

Water from major rivers in the upper reach of Indus Basin and run off from Baluchistan Plateau join Indus River in central part of Indus Basin. All barrages located below this point are generally more affected. Table 2, shows design capacity and flow levels of 2010 Flood at these barrages. It is obvious from this data that the flood flowed through Guddu and Sukhar inflicting high hydraulic stresses while at Kotri Barrage, the flow was more than the design flow. In all circumstances these flood levels are classified as "super". Geotechnical and structural investigations are now an absolute necessity to review the need to strengthen these structures against future flood risks.

Table 2. Flow levels of 2010 Flood in southern part of Indus Basin (Amir, 2010)

Barrage Location	Design Flow (Lac Cusec)	2010 Flood Flow (Lac Cusec)
Guddu	12	11.48
Sukhar	15	11.30
Kotri	8.75	9.64

INVENTORY OF RECENT FLOODS AND NATURAL HAZARDS

Owing to the various natural factors described earlier, Pakistan has witnessed numerous natural disasters during its recent history. Figures 11show an inventory of major hazards of the recent history and people affected. Floods are highest on the list, affecting approximately 55 million people to date.

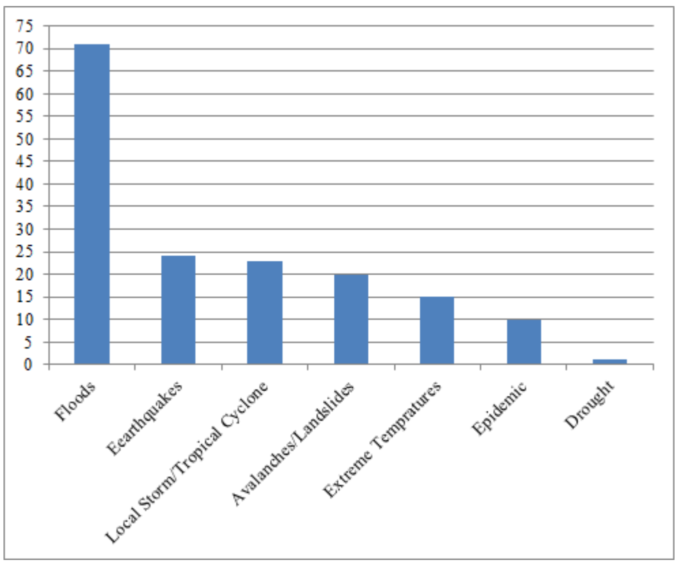

Fig.11. Natural Disasters in the recent history of Pakistan (source: United Nations Office for the Coordination of Humanitarian Affairs)

COMPARISON OF HISTORIC FLOOD LOSSES

Comparison of flood Losses since last 60 Years and 2010 Flood are given in Figure 12 and Table 3 (Flood Report 2010, Federal Flood Commission, Ministry of Water and Power, Pakistan, 2010). The 2010 flood which started in July in Northern areas persisted till August 2010 in Southern part of Indus basin, was equally damaging throughout the basin, Figures 13 through 15.

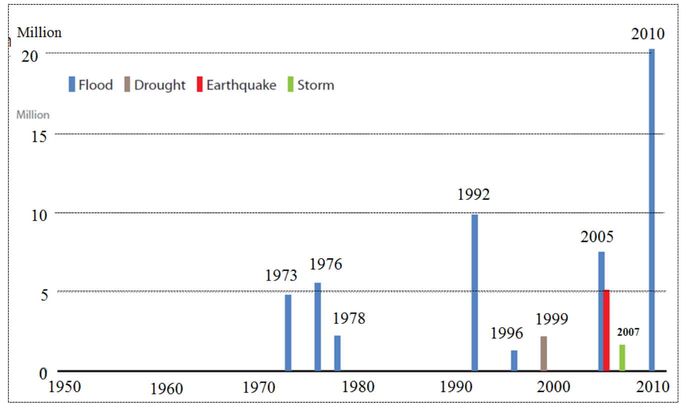

Fig. 12. Natural hazards vis-à-vis number of people affected

Table 3. Summary of flood losses in recent history

Category of Loss	Past 60 Years Floods	2010 Floods
Cumulative financial losses	US$ 30.00 Billion	US$ 10.00 Billion
Public lives lost	8887	2000
People Affected	55 Million	20 Million
Villages destroyed/damaged	109822	17553
Area affected	407132 km^2	160,000 km^2

Fig. 13. Gushing floodwater at the foot hills of Hindu Kush Ranges (FFC report, 2010)

Fig. 14. Flood at Nowshera, KPK (FFC report, 2010)

Fig. 15. Flood in an area near Kotri Barrage, southern end of Indus Basin (FFC report, 2010)

FLOOD CONTROL AND PROTECTIVE SYSTEM

Major components of flood control and protection systems in Indus Basin are listed in Table 4 (Flood Report 2010, Federal Flood Commission, Ministry of Water and Power, Pakistan, 2010).

Table 4. Flood protection system

Flood Protection Component	Number
Major storage reservoirs with cumulative storage capacity of 14.1 Million Acre Feet	3
Dams of all category	143
Barrages (weirs)	19
Link canals to shift water from one area to another for irrigation and flood control	12
Spurs	1410
Flood protection embankments	6803 km

Lower part of Indus River, has more potential of risk to public lives, property and infrastructure. This stretch of the river is protected with flood protective embankments as shown in Figure 16.

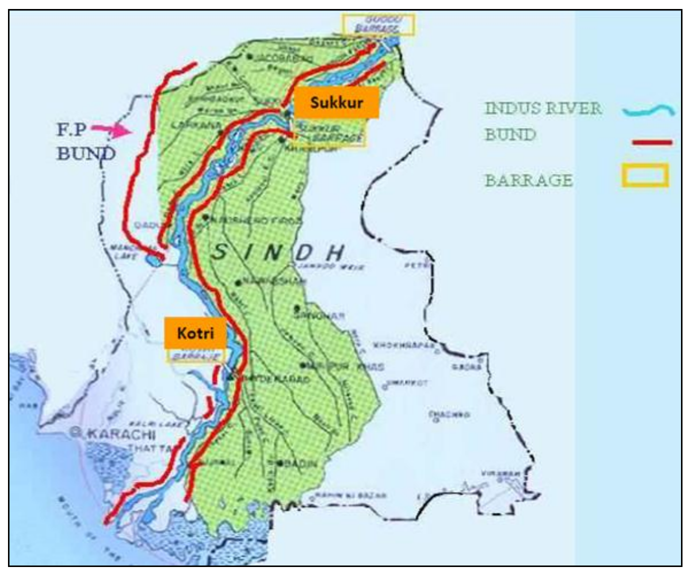

Fig.16. Flood Protective embankments shown in red color along River Indus in southern part of Indus Basin (WAPDA Report, 2010)

Inadequate discharge capacity of hydraulic structures in the Indus basin including barrages, road and rail bridges causes water to pond and eventually creating flood conditions. Lack of spatial planning and understanding of future flooding risks are the reasons attributed the inadequate drainage capacities. This factor causes damage to roads, railway lines, bridges in two ways; firstly, during water saturation stage in terms of differential settlements and secondly, during breaching stage in terms of partial or complete destruction of structures.

Due to limited water in River Chenab and Sutlej since couple of decades, active flood plains of these rivers have been inhabited extensively. Such population is mostly poor and do not have the option of re-settlement in other expensive areas. In case of heavy rains, constricted water courses results in flooding of rivers and immediate vicinities with consequent damage to lives and infrastructure. During 2010 Flood, population in active flood plains was affected equally at start and terminal parts of Indus Basin.

FLOOD CONTROL AND MANAGEMENT MECHANISM

Sequel to substantial losses during floods of 1973 and 1976, responsibility of flood management was shifted to Federal Government. In 1977, Federal Flood Commission (FFC) was formed to ensure comprehensive flood management policies (Flood Report 2010, Federal Flood Commission, Ministry of Water and Power, Pakistan, 2010). FFC formulated four major National Flood Protection Programs. So far, three programs have been implemented at a cost of Rupees 26.138 Billion which included flood protection infrastructure and flood forecasting & warning systems. Fourth program which commenced in 2008 is likely to complete in 2018.

As per its charter, FFC remains operative round the clock during flood season each year from July to October. Before the onset of flood season, a flood control meeting of stakeholders (Federal & Provincial Administration, Police, Military, Meteorological, Water & Power Ministry, etc.) is held in the capital, a network of flood control centers is activated in the entire country. A Flood Situation Report is issued on daily basis to keep all stake holders updated on the situation. FFC regulates guidelines/procedures for following:

- Safety of dams
- Safety of barrages
- Demolition of flood embankments to save cities and hydraulic structures or to divert water to flood reservations
- Breaching of river/canals to avoid damage to critical bridges/structures

EFFICACY OF FLOOD CONTROL AND PROTECTIVE INFRASTRUCTURE

Flood management system of Pakistan established since 1977 with comprehensive country wide network of forecasting, monitoring, and protective measures should have performed much better than what has been observed in the recent past.
Most of the protective infrastructure is built with normal soil and stone/brick masonry. The large number of failure of these embankments is an indicative of inappropriate materials and quality controls, Figures 17 through 20. It is also evident that reinforced layer of embankments comprised of poor quality bags placed in a non-engineered framework, Figure 19. The entire control and protective mechanism need a complete geotechnical re-appraisal encompassing design concepts, construction materials, construction techniques, maintenance procedures and rehabilitation strategies.

Fig.17 Flood protection embankment; an evidence of inadequate construction material and poor finished quality (Amir, 2010)

Fig. 18 Flood protection embankments with inadequate construction material and poor finished quality (Amir, 2010)

Although, flooding of susceptible areas is unavoidable, loss of large number of public lives is a clear indicator of shortfalls in forecasting, coordination among flood management tiers, regional and spatial hydrological behavior of Indus Basin. Failure of flood protection embankments is also a black spot and necessitates innovation in design concepts, construction materials and their orientation with respect to future flooding phenomenon. The devastation caused by recent floods demands for more refined forecasting & warning systems, and coordination among all stakeholders.

Fig.19. A rehabilitated flood protection embankment showing fate of construction material and quality of embankment to face future floods (Amir, 2010)

Fig.20 Stone masonry flood protection embankment at a critical location showing poor construction quality (Amir, 2010)

A mega drainage project Right Bank Out Fall Drain (RBOD) and Left Bank Out Fall Drain (LBOD) are located in lower part of the Indus Basin with a purpose of drain surface run off of Baluchistan Plateau and brackish ground water of the surroundings. During 2010 Floods, embankments of RBOD and LBOD were washed away and caused damage to local property. The quality of these embankments remained questionable and needs a review of construction materials and techniques, Figures 21 through 23.

Fig.21 An earthen embankment of RBOD (Amir, 2010)

Fig.22 Fate of earthen embankment of RBOD during 2010 floods (Amir, 2010)

Fig.23 Rehabilitation of embankment of RBOD for future floods, the material and method adopted makes its efficacy doubtful (Amir, 2010)

LESSONS LEARNT

The quantum of losses during 2010 Flood left us with serious questions on reliability of flood forecasting and warning mechanism, location and orientation of flood protective components, construction materials and techniques for flood control & protective infrastructure, and flood hazard mitigation. The fate of conventional flood control and protective infrastructure built over last few decades costing billions of rupees is a testimony that modern GIS based spatial regional and urban planning, reinforced earth systems, and reliable forecasting & warning systems are the only option to face the future floods. 2010 Flood has left us with number of lessons to prepare for the worst. Some of the lessons are:

- To ensure safety of public lives and infrastructure, flood defense system must continually be monitored, improved and enhanced.
- Keeping in view economic constraints, innovative and sustainable flood defense systems with least maintenance cost should be evolved.
- Keeping in view poor performance of flood defense systems, it is now obvious that existing design concepts, construction materials, maintenance routines, etc. need to be reviewed and revised.
- The future defense systems must include reinforced earth systems, bio-engineered systems, rehabilitation of existing dykes etc.
- The storage systems should also have pneumatic weir at the critical locations to allow regulating the flood water during and after the floods for useful purposes. In view of enormous cost of such systems, plans should be prioritized for short and long term implementation.
- The flood systems should include a combination of hydraulic storage (flood control reservation and dry dams), self-closing flood barriers, hydraulic structural systems and flood diversions.
- Along Indus River, vast areas are available within flood plains in the shape of barren lands which should be converted into hydraulic storage systems. These should be spatially analyzed for location suitability and efficient storage. These should be protected with bio-engineered and reinforced earthen components.
- In areas along the rivers susceptible to flooding hazard, more robust flood protective dykes should be provided. In view of the deforestation and large number of household construction in the flood plains, GIS based spatial study should be performed to identify location of such dykes.
- Formulation of flood risk assessment and management system comprising:
    - Climate change
    - Drainage infrastructure
    - Regional Urban planning
    - Management stakeholders

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